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VISIBLE MAGNITUDE OF TYPICAL SATELLITES
IN SYNCHRONOUS ORBITS

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The references for Technical Note 1974-23 (W. E. Krag, "Visible Magnitude of Typical Satellites in Synchronous Orbits," 6 September 1974) are listed below. They were inadvertently omitted from that report.

1. G. A. McCue, J. G. Williams and J. M. Morford, "Optical Characteristics of Artificial Satellites," Planet. Space Sci. 19, 851 (1971).
2. J. N. Hamilton, "Radiometry of Objects in Space," Report No. TOR-0073(3486)-1, Aerospace Corporation, El Segundo, California (1972).
3. V. Slabinski, private communication.
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6. W. E. Krag, R. Sridharan and A. J. Yakutis, "A Simple Technique for Recording Optical Signatures," Technical Note 1974-18, Lincoln Laboratory, M. I. T. (20 March 1974), DDC AD 777152/0.
7. R. T. Prosser, "The Lincoln Calibration Sphere," Proc. IEEE (Correspondence) 53, 1672 (1965), DDC AD 457238.
8. IMP-6 First Year Report, Goddard Space Flight Center, Greenbelt, Maryland (March 1972).

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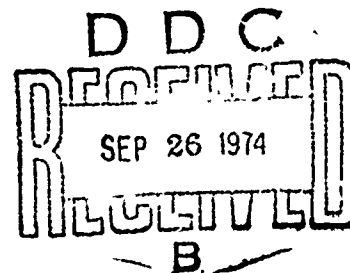
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

VISIBLE MAGNITUDE OF TYPICAL SATELLITES
IN SYNCHRONOUS ORBITS

W. E. KRAG
Group 96

TECHNICAL NOTE 1974-23

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ABSTRACT

Expressions for the visibility, in terms of visible magnitude, of resident space objects are presented in this report. The variations of the visible magnitude with the geometry of the viewing situation, considering variables such as distance, surface type and reflectivity, viewing angles, and spacecraft orientation, are discussed. Calculations of the visible magnitude to be expected and some of the variations are then made for typical satellites in synchronous orbits. Finally, calculations of the maximum visible magnitudes for several satellites, with a collection of the available data and some photographs are presented in an appendix.

This work is related to the Telescope Detection and Ranging (TDAR) Program.

VISIBLE MAGNITUDE OF TYPICAL SATELLITES IN SYNCHRONOUS ORBITS

A significant effort is being made at Lincoln Laboratory, and at other installations both in and out of the Air Force, to locate, and observe the optical characteristics of, Resident Space Objects (RSOs). Large, low-orbit satellites have been observed extensively¹ and calculations have been made of the visible magnitude of these objects. Only recently, however, has it been possible to consider the use of rather large telescopes and sophisticated detectors for those observation of satellites of typical size and construction in synchronous orbits. For these conditions the visibility is expected to be low and well beyond the capability of the naked eye. The calculations given in this report show the maximum visibilities which can be expected from typical satellites in synchronous orbits under ideal conditions. The report is part of a preliminary study for the Telescope Detection and Ranging (TDAR) Program, which was, until recently, supported by the general research funds of the Laboratory.

The visible magnitudes of simple objects such as spheres, cylinders, flat planar objects, and cones illuminated by solar irradiation can be calculated in a straightforward manner. It is necessary to set up a coordinate system relating the sun, the RSO and the observer, defining the phase angle, as well as the orientation of the RSO with respect to both the sun and the observer.

A table of functions for the visual magnitudes for spheres, cylinders, and plates illuminated by the sun has been compiled by McCue, et al.¹ and is presented in Table I.

In using Table I, the phase angle, Φ , is a function of observer-RSO-sun angle, θ , and can be calculated from the expression

$$\cos \Phi = \sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos \theta$$

where ϕ_1 and ϕ_2 are the latitudes of the sun and the observer from the principal axis of the RSO. In Figure 1, which shows the geometry, the RSO is located at the

TABLE I
PHASE FUNCTIONS FOR SPECULAR AND DIFFUSE SPHERES, CYLINDERS AND FLAT PLATES

Shape	Reflection	$F(\phi)$	Remarks	Reference	
Sphere	Specular	$\frac{1}{4\pi}$		a	
	Diffuse	$\frac{2}{3\pi} \{(\pi - \phi) \cos \phi + \sin \phi\}$		b	
Cylinder	Specular	$\frac{\cos(\theta/2) \alpha(t)}{4\Delta}$	Δ is width of reflected fan of light (≥ 0.0093 rad)	c	
		$\frac{\alpha(t)}{4\Delta}$	$ \phi_1 + \phi_2 \leq \Delta/2$ for flash		
	$\frac{\cos(\phi/2) \alpha(t)}{4\Delta}$	$\alpha(t) = \frac{3}{\pi} \sqrt{\frac{t}{t_0} \left(1 - \frac{t}{t_0}\right)}$ during flash			
	$\frac{\cos \phi_1 \cos \phi_2}{4\pi}$	0 otherwise ($t \geq t_0$)			
	$\frac{\cos^2(\phi/2)}{4}$	Maximum flash			
	$\frac{1}{4\pi} \{(\pi - \theta) \cos \theta + \sin \theta\}$	Minimum flash			
Flat Plate	Specular	$\frac{1}{4\pi} \{(\pi - \phi) \cos \phi + \sin \phi\}$	Maximum	d	
		0	Intermediate value		
	Diffuse	$\frac{4 \cos(\phi/2)}{\pi \Delta^2}$	Minimum		c
		0	During flash ($ \phi_1 - \phi_2 \leq \Delta/2, \theta = \pi/2$)		
	$\frac{1}{\pi} \sin \phi_1 \sin \phi_2$	Δ is width of reflected beam (≥ 0.0093 rad)			
	$\frac{1}{\pi} \cos^2(\phi/2)$	No flash			
		ϕ_1 and ϕ_2 same signs			
		ϕ_1 and ϕ_2 different signs			
		Maximum			

- a. R. Toussay, J. Opt. Soc. Am., 47, 261 (1957).
b. H. N. Russell, Ap. J., 43, 173 (1916).
c. R. H. Glees, SAO Special Report No. 127 (1963).
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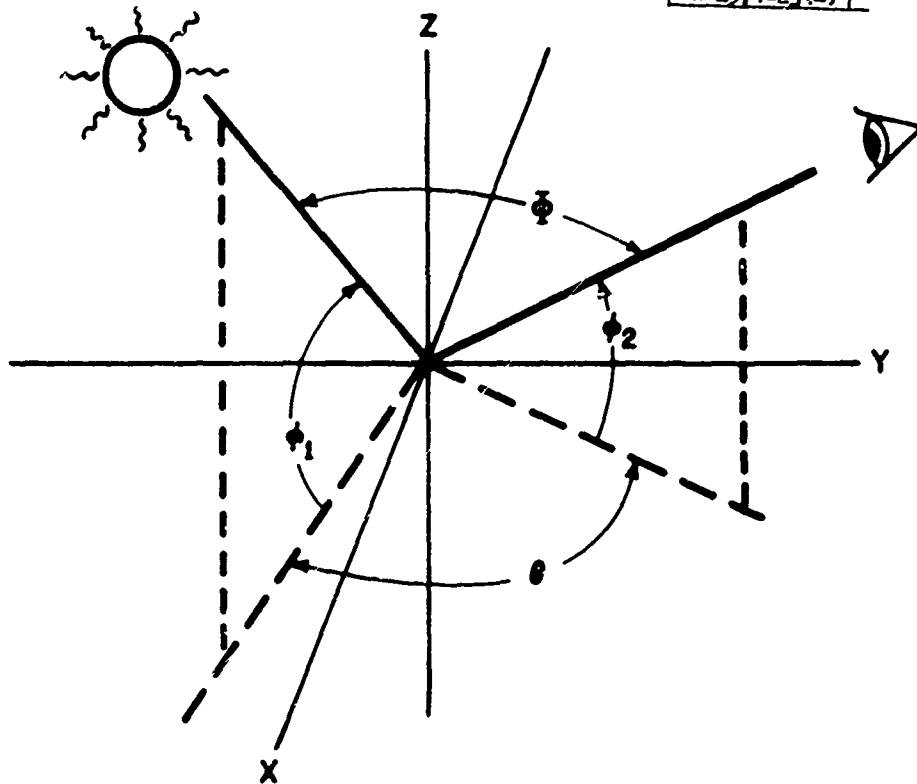


Fig. 1. Coordinate system for Table I. In Table I, R is the observer to satellite distance. The satellite is located at the origin. For the expressions in Table I, a cylinder is oriented with its axis along the polar axis and centered on the origin and a flat plate is centered with its normal along the polar axis. The latitudes of the sun and the observer respectively are ϕ_1 and ϕ_2 , and θ is the difference in longitude.

origin of the coordinate system. In the special cases of a sphere and a cylinder with its polar axis normal to the sun-RSO-observer plane, $\Phi = \theta$.

The visual magnitude is calculated from the expression

$$m_v = -26.78 - 2.5 \log \frac{\rho A F(\Phi)}{R^2}$$

where ρA is the reflectivity-area product, $F(\Phi)$ is from Table I, and R is the observer to satellite distance. The visual magnitude of the sun is -26.78 , uncorrected for atmospheric effects. The visual magnitudes become more positive as the RSO becomes less bright (R is, by far, the dominant factor for satellite size objects).

There are several interesting features to be noted from Table I. Diffusely reflecting satellites at full phase with the same ρA product have magnitudes which vary $< \pm 1$. The specular flash from a flat plate, on the other hand, can be orders of magnitude brighter ($\approx 11 m_v$) than any diffuse reflector of the same area.

The specularly reflecting sphere is the dimmest object [for a given ρA and ignoring cases where $F(\Phi) = 0$], but it has the interesting property of having a magnitude which is independent of phase angle.

Hamilton² has prepared analytic expressions and plotted magnitude calculations for RSOs with the above shapes plus the cone and spherical segments, which are useful in these calculations.

Figure 2, taken from McCue¹, shows the variation with phase angle of the absolute magnitude for an object with a reflectivity-area product of $\rho A = 1 \text{ m}^2$ located at a distance R of 37,100 km ($1 \times$ synchronous orbit). The ordinate in the figure could be labeled in terms of $\Delta m_v(\theta) = -2.5 \log F(\Phi)$, to show the same information.

For the cases plotted, m_v increases by one as the phase angle changes from 0° to 90° . For the case of a flat plate at the zenith and with the normal to the plate directed at the observer, the diffusely reflected radiation reaching the observer goes to zero at a phase angle of 90° .

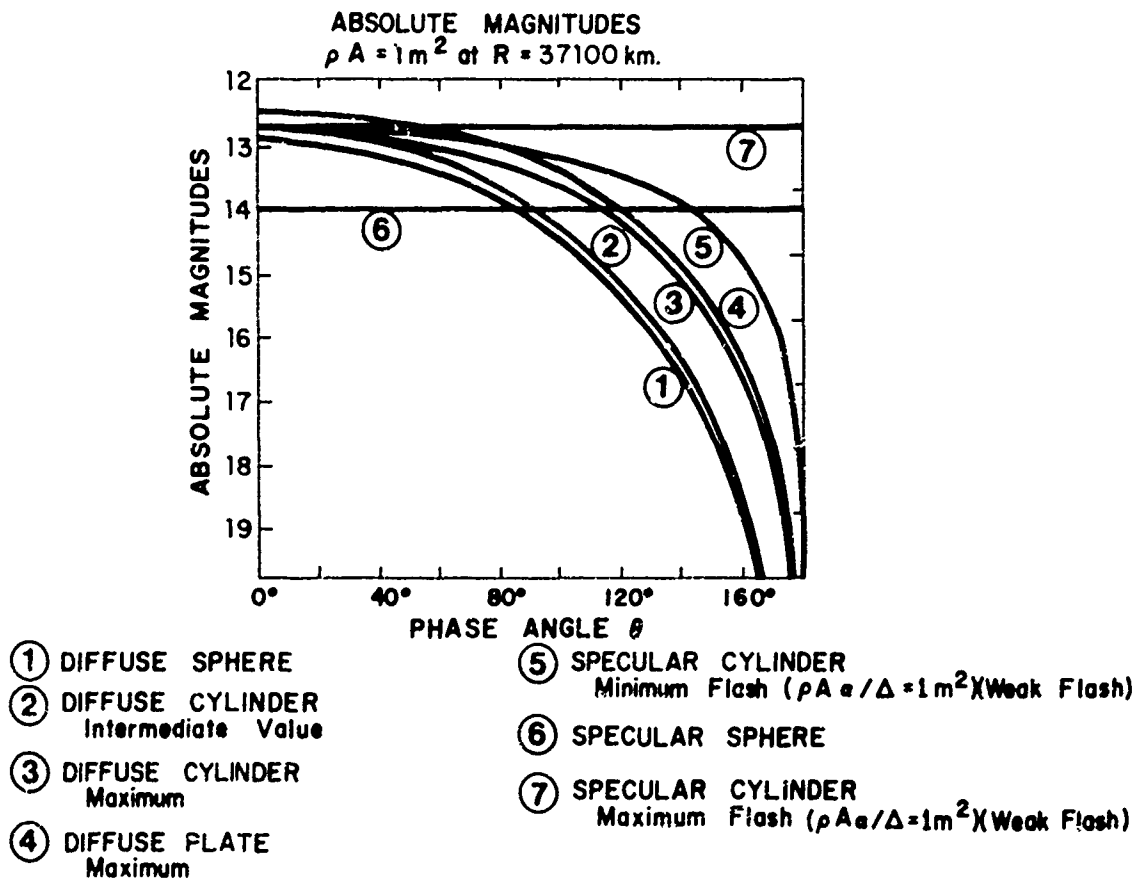
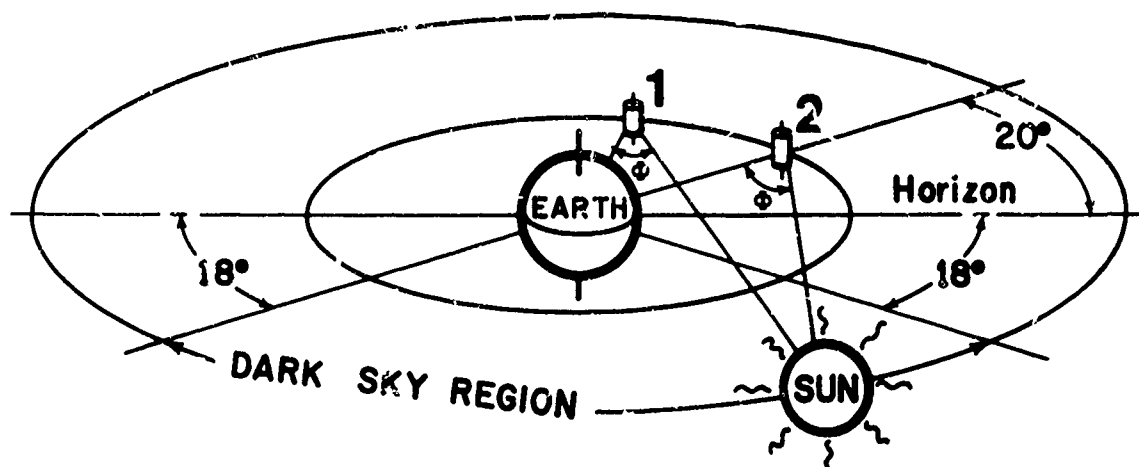


Fig. 2. Theoretical determination of absolute magnitude as a function of phase angle.

Figure 3 shows the phase angle variation of the visible magnitude for a stationary, cylindrical RSO in a synchronous equatorial orbit with its polar axis normal to its orbit with typical observation conditions. As indicated in the figure, when the sun is 18° or more below the horizon, the night sky has minimum brightness. This is the "dark sky region." Objects less than 20° above the horizon are difficult to observe, because of the increased air mass the reflected light must traverse. This affects the observations because of the probability of increased "seeing" difficulties and because of a larger extinction coefficient due to the increased air mass. For a satellite at the zenith, the phase angle varies from 72° when the sun is 18° below the horizon to 0° at local midnight (assuming no eclipse) to 72° when the sun is about to rise. This is case 1 in Figure 3. Then Φ is less than 72° and the phase function correction to the visible magnitude, $\Delta m_v = -2.5 \log F(\Phi)$, varies between 1.51 and 1.97 magnitudes or less than a half magnitude variation. On the other hand, as shown in case 2, when the satellite is 20° above the horizon, Φ varies from $180^\circ - 20^\circ - 18^\circ = 142^\circ$ when the sun is near the same horizon as the satellite, through 0° and up to 2° when they are on opposite horizons. In this case, Δm_v varies between 1.51 and 3.94 magnitudes, a total change of almost 2.5 magnitudes.

In addition to the corrections which have to be made for phase angle, listed in Table I, the specular reflections, in particular, are extremely dependent on the perfection of the surface flatness. For example, the observed specular reflection from a line of solar cells could decrease by more than four magnitudes if the normals to the solar cell surfaces were dispersed over one degree.² This extreme dependence is due to the small angle of the sun's image as viewed from the earth.

In calculating the specular reflections, the visible magnitudes are calculated assuming that only one specular reflection will be observed at any given moment. For diffuse reflection, on the other hand, radiation is reflected from all surfaces in the direction of the observer and the radiation has to be summed from all surfaces. The equation for the visible magnitude becomes in that case:



$$\Delta m_v = -2.5 \log F(\Phi) = -2.5 \log \frac{1}{4} \cos^2 \frac{\Phi}{2}$$

1: AT ZENITH: $\Phi < 72^\circ$ AND $1.51 < \Delta m_v < 1.97$

2: 20° ABOVE HORIZON: $\Phi < 142^\circ$ AND $1.51 < \Delta m_v < 3.94$

Fig. 3. Phase functions for synchronous, cylindrical RSOs.

$$m_v = -26.78 - 2.5 \log \sum \frac{\rho A F(\Phi)}{R^2} ,$$

where $\rho A F(\Phi)$ is calculated separately for each surface.

In Figure 4, the calculated visible magnitudes for various RSOs are given. Shown in the center are sketches of typical objects, and at the right and left, respectively, the visible magnitudes for diffuse and specular reflection. The calculations are made for objects in full phase, at zenith, and no correction is made for atmospheric absorption. These are, therefore, the maximum visibilities which could be expected for the various objects.

Intelsat IIIF-2 has a main body, a cylinder, covered by solar cells. This body gives a magnitude of 15^m . The diffuse reflection of the folded-horn despun antenna, plus the reflection of the squat black cylinder between the main body and the antenna, is estimated to add enough radiation to raise the visible magnitude to $14^m.6$.³ With the IVF-3, there is a similar situation; however, the parabolic antennas are painted black and there is very little reflection from them. The feed horns are covered with metallized Mylar sheet for thermal protection. This material is highly reflecting and highly crinkled, so it contributes a significant amount of diffuse reflection.³ The total visible magnitude is given in the figure. It will be realized, of course, that the phase angle variation of the visible magnitude will be different for the cylindrical main body than it is for the semiflat area of the antennas.

This phase angle dependence is shown by consideration of the IVF-3 satellite. The phase angle dependence of the diffuse reflection from the main cylinder changes by only a factor of 2 when the sun-RSO-observer angle changes from 0 to 90 degrees. For the antennas, however, the diffuse reflection toward the observer when the sun is in plane of the antenna surface goes to zero.

In the appendix which follows, sketches and photographs, when available, and simple calculations of visible magnitude are presented for various satellites.



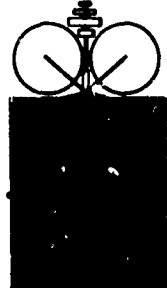

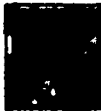
SPECULAR	RSO	DIFFUSE
14 ^m 2	SPHERE $\sigma A = 1\text{m}^2$  $\rho_{\text{DIFFUSE}} = 1$ $\rho_{\text{SPECULAR}} = 1$	13 ^m 1
13 ^m 7	INTELSAT III F-2 56' DIA x 41" LONG  SOLAR CELLS 1" x 41"	12 ^m 6
5 ^m 8	INTELSAT III F-3 93.7 DIA x 111" LONG ANTENNAS 40" DIA. BLACK  SOLAR CELLS 1" x 111"	12 ^m 8
8 ^m 0	LES-6 49" DIA x 66" LONG  SOLAR CELLS 2 cm x 43 cm	13 ^m 8
6 ^m 6	ATS-1 6 ^m 6 14 ^m 5 58 IN DIA x 53 IN LONG  SOLAR CELLS 2 cm x 1.35 m	14 ^m 5

Fig. 4. Visible magnitudes of "typical" satellites in $1 \times$ synchronous orbits. Satellites are viewed full phase and at zenith ($R = 37,100$ km). For solar cells, $\rho_{\text{diffuse}} = 0.07$, $\rho_{\text{specular}} = 0.15$.

ACKNOWLEDGMENTS

The author wishes to thank R. Sridharan for his assistance in obtaining information about the satellites discussed in this report and Dr. V. Slabinski of Comsat Corporation for details on the Intelsat satellites, as well as an enlightening discussion of the effects which would be expected in the observations. The author also wishes to acknowledge the typing assistance of Mrs. Katherine A. Fellows.

APPENDIX A

In this appendix we describe, briefly, the physical structure of various RSOs, particularly with regard to the physical characteristics as they affect the sunlight scattered toward the observer on earth. We then calculate the visible magnitude expected for the RSO at zenith and for the full phase condition. This, for diffusely reflected radiation, is the maximum expected visibility. Specular reflections, which are not regularly observed, are treated as special cases and not added to the diffuse reflection. A group of RSOs in $1 \times$ synchronous orbit will be considered first, and then calculations presented for a few synchronous satellites with different orbital parameters.

For all of the calculations we shall assume³ that the diffuse reflection coefficient is 0.07 and the specular reflection coefficient is 0.15 for all solar cells. For most other surfaces, except where noted, estimates of the reflection coefficient will be used.

INTELSAT IIIF-2

Intelsat IIIF-2 (Satellite Identification No. 3623)⁴ is in a $1 \times$ synchronous, approximately stationary equatorial orbit, located at longitude 258 East. A photograph of the satellite is shown in Figure A1. The IIIF-2's main body is rotating at ≈ 0.7 sec/rev around the polar axis, with the polar axis approximately normal to the orbit plane. The polar axis describes a 1° cone about the spin axis. The body is a cylinder 41" (1.04 m) long with a 56" (1.42 m) diameter and the circumference is covered with solar cells. The solar cells are glued to the surface in columns in a shingled fashion, with alternate columns shingled up and down. The solar cell normals are at 88.7° and 91.3° with respect to the polar axis, with a 1° to 2° variation in the normals. The despun antenna horn is covered with specularly reflecting Al coated mylar, with a small effective diffuse reflection coefficient and the horn (28 cm \times 30 cm diameter) itself has a diffuse reflection coefficient of 0.52. The squat cylinder and the omni-antenna under the cone has a reflectivity area product of $\approx 0.002 \text{ m}^2$.

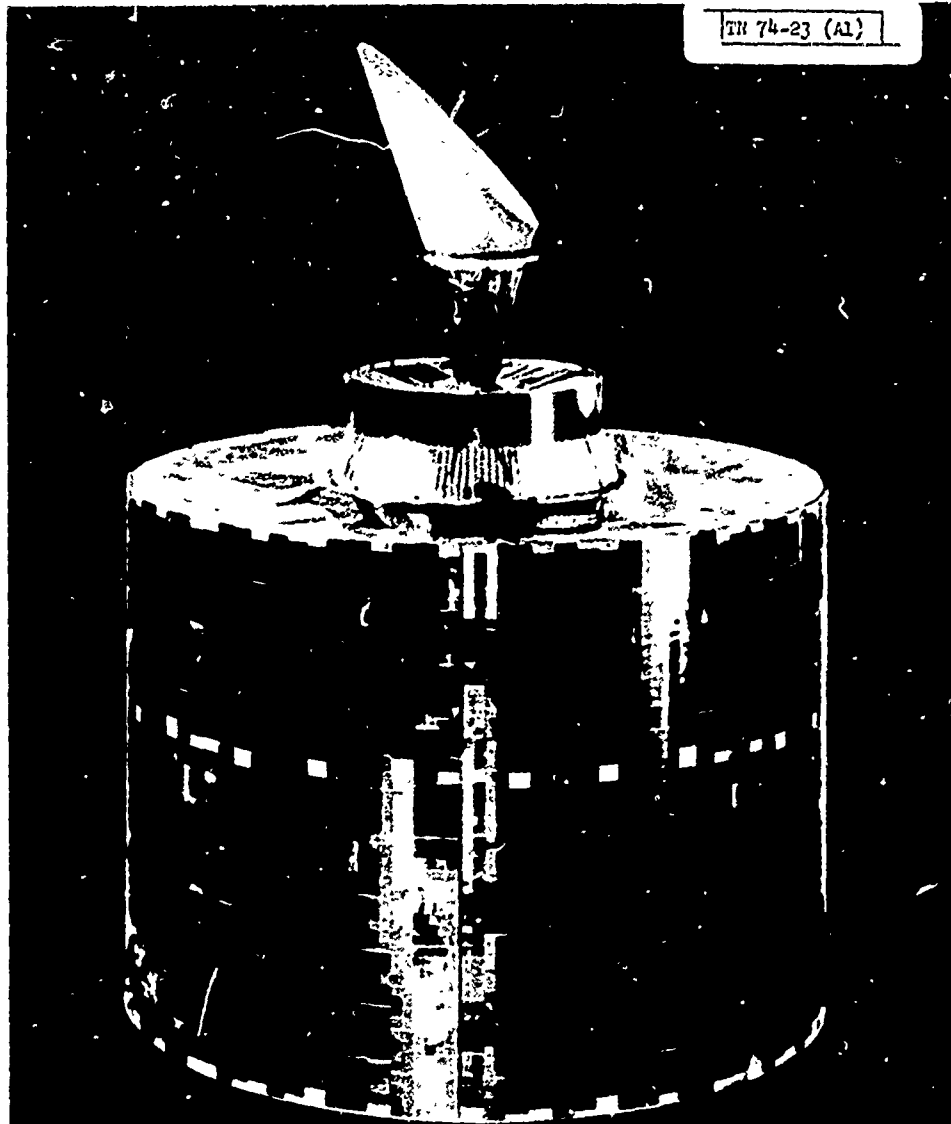


Fig. A1. Intelsat III F-2 Satellite. (Reprinted with permission of Communications Satellite Corporation, Washington, D. C.)

The visible magnitude is then

$$m_v = -26.78 + 5 \log R - 2.5 \log \rho A - 2.5 \log F(\Phi)$$

$$m_v = -26.78 + 5 \log 3.71 \times 10^7 \text{ m} - 2.5 \log \rho A F(\Phi)$$

$$m_v = 11.07 - 2.5 \log \rho A F(\Phi).$$

Consider first the diffuse reflection.

For the main cylinder

$$\rho A F(\Phi) = .07 \times 1.04 \times 1.42 \times 1/4 = .0258 \text{ m}^2.$$

The horn aperture, considered as a flat plate, has a reflectivity area product of

$$\rho A = .52 \times .28 \times 0.30 = .0437 \text{ m}^2, \text{ giving}$$

$$\rho A F(\Phi) = .0437 \times 1/\pi = .0139 \text{ m}^2,$$

while for the low cylinder

$$\rho A F(\Phi) = .002 \times 1/4 = .0005 \text{ m}^2.$$

Then

$$m_v = 11.07 - 2.5 \log \{ .0258 + .0139 + .0005 \}$$

$$m_v = 14.6$$

is the visible magnitude of the diffusely reflected solar radiation.

Now for specular reflection from a line of solar cells 2 cm wide and 1.42 m long

$$\rho A F(\Phi) = .15 \times .02 \times 1.42 \times \frac{4}{\pi (.0093)^2} =$$

$$= 62.71$$

giving

$$m_v = 11.07 - 2.5 \log 62.71$$

$$m_v = 6.6^m$$

This, of course, is a very bright reflection. However, with a $1^\circ - 2^\circ$ variation in solar cell normals, the intensity decreases² by 4 to 6 magnitudes.

NOTE: Virtually all of the information on the Intelsat satellites was graciously supplied by V. Slabinski of the Comsat Corporation. Dr. Slabinski also pointed out the antireflection-coated silicon solar cells reflect a large fraction of the incident ultraviolet light. This means that the measured magnitudes are a function of the spectral sensitivity of the detectors. Since photographic film and most photocathodes are more sensitive than the eye to ultraviolet light, the measured magnitude of a satellite image is likely to be higher than the visually observed, and calculated above, magnitude.

INTELSAT IVF-3

Intelsat IVF-3 (Satellite Identification No. 5709)⁴ is in a $1 \times$ synchronous, approximately stationary equatorial orbit located at Longitude 336.6° East. The polar axis of the cylinder is normal to the orbit plane. A photograph of one of the Intelsat IV satellites, whose surface coatings were varied on some of the satellites, is shown in Figure A2. The main cylinder is 141" (2.82 m) long and 93.7" (2.38 m) in diameter and covered with solar cells. The solar cells are not shingled. The antennas are ≈ 50 " (1.27 m) in diameter with a diffuse reflectivity of ≈ 5 percent. The feed horns are covered with a highly crinkled gold-colored insulation and are approximately 3' (1 m) long and have a diameter of 6" (15 cm). Calculating the visible magnitude due to the diffuse reflection,

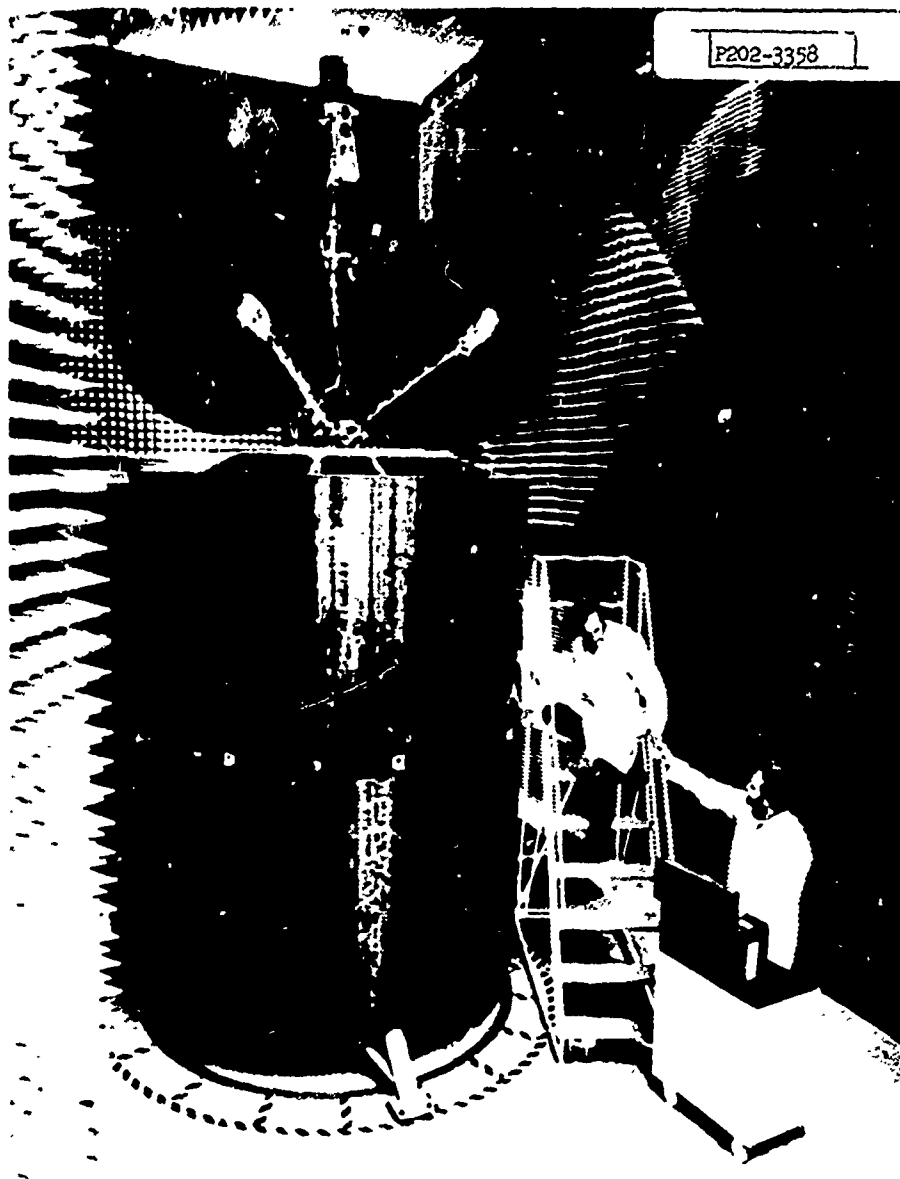


Fig. A2. Photograph of Intelsat IVF Satellite. (Reprinted with permission of Communications Satellite Corporation, Washington, D. C.)

$$\rho A F(\Phi) = .07 \times 2.82 \times 2.38 \times 1/4$$

$$= 0.117 \text{ m}^2 \text{ for the solar cells,}$$

$$\rho A F(\Phi) = 2 \times 0.05 \times \frac{\pi (1.27)^2}{4} \times 1/\pi$$

$$= .020 \text{ m}^2 \text{ for the two antenna considered as flat plates, and}$$

$$\rho A F(\Phi) = 2 \times .9 \times 1 \times .15 \times 1/4 = .0675 \text{ m}^2 \text{ for the two feed horns,}$$

for a total (diffuse) visible magnitude of

$$m_v = 11.07 - 2.5 \log [0.117 + 0.020 + 0.0675]$$

$$m_v = 12.8$$

It appears unlikely that the antenna structure located between the two large antennas will contribute significantly to the diffuse reflection.

The specular reflection from a line of solar cells gives

$$\rho A F(\Phi) = 0.15 \times .02 \times 2.82 \times \frac{4}{\pi (.0093)^2}$$

$$= 124.5, \text{ and a visible magnitude of}$$

$$m_v = 11.07 - 2.5 \log 124.5$$

$$= 5.8$$

As in all the calculations in this report, the specular reflection is expected to be decreased by several magnitudes because of dispersion of the solar cell normals.

APPLICATION TECHNOLOGY SATELLITES⁵

Application Technology Satellite -1 (ATS-1) is in a 1 × synchronous, approximately stationary equatorial orbit located at longitude 149.1 West (Satellite Identification No. 2608).⁴ ATS-3 (Satellite Identification No. 3029)⁴ is a similar satellite, located at longitude 69.1 West. An artist's conception of the satellite is shown in Figure A3. These satellites are oriented with their polar axes normal to the orbit plane. The cylindrical bodes are 1.47 m in diameter, 1.35 m in length, and are covered with panels of solar cells. There are no large antenna structures on the satellites, so the visibility calculation concerns only the solar panels. For these

$$\rho A F (\Phi) = .07 \times 1.47 \times 1.35 \times \frac{1}{\pi} = .0442 \text{ m}^2$$

and

$$m_v = 11.07 - 2.5 \log .0442 = 14.5^m$$

is the visible magnitude of the diffuse reflection from the solar cells. The specular reflection gives, for a line of solar cells 2 cm wide by 1.35 m long

$$m_v = 11.07 - 2.5 \log .15 \times .02 \times 1.35 \times \frac{4}{\pi (.0093)^2}$$

$$m_v = 6.6^m$$

ATS-5 (Satellite Identification No. 4068)⁴ like the ATS-1 and ATS-3 satellites is in a 1 × synchronous, approximately stationary equatorial orbit located at longitude 105° West. ATS-5 is a cylindrical satellite, rotating at a rate of 0.8 sec/rev, 1.83 m long and 1.43 m in diameter, with its polar axis approximately normal to the orbit plane. It has two cylindrical banks of solar cells each approximately 0.6 m long.



Fig. A3. Artist's conception of ATS-1 and ATS-3 Satellites. (Reprinted with permission of NASA.)

The middle third of the satellite, as shown in Figure A4, is occupied by various planar array antennas. The precise dimensions and reflectivities of the planar arrays are not known to the author but we estimate a diffuse reflection coefficient of 0.5 with dimensions of 0.4×0.3 m for the largest array and a total area for the arrays 50 percent larger.

We assume that the black area in the central section has a diffuse reflection coefficient of 0.03.

Thus, considering the diffuse reflections,

$$\rho A F(\Phi) = 2 \times .07 \times 1.43 \times 0.6 \times \frac{1}{\pi} = .0300 \text{ m}^2$$

for the two banks of solar cells,

$$\rho A F(\Phi) = .03 \times 1.43 \times .6 \times \frac{1}{\pi} = .0051 \text{ m}^2$$

for the black band, and

$$\rho A F(\Phi) = 1.5 \left(0.5 \times 0.4 \times 0.3 \times \frac{1}{\pi} \right) = .0286 \text{ m}^2$$

for the total planar array area. This gives

$$m_v = 11.07 - 2.5 \log [.0300 + .0051 + 0.0286]$$

$$m_v = 14.1$$

for the visible magnitude of diffuse reflection.

From a single bank of solar cells, the specular reflection gives a magnitude of

$$m_v = 11.07 - 2.5 \log \left[.15 \times .02 \times .6 \times \frac{4}{\pi (.0093)^2} \right]$$



Fig. A4. Photograph of center section, ATS-5 Satellite. (Reprinted with permission of NASA.)

$$m_v = 7.5$$

The previously mentioned factors affecting the specular reflection should be kept in mind in evaluating the magnitude of these specular reflections.

The specular reflections from the planar arrays are difficult to estimate. However, let us assume that only one array contributes to a particular beam, that 50 percent of the area reflects 20 percent of the incident sunlight in a specular direction, and calculate the magnitude for only the largest array. Then

$$m_v = 11.07 - 2.5 \log \left[0.5 \left(0.2 \times 0.4 \times 0.3 \times \frac{4}{\pi (.0093)^2} \right) \right]$$

$$m_v = 5.5$$

We make no estimate of the dispersion of the array normals over the surface.

NOTE: A more complete discussion of the image intensity of the ATS-5 satellite, including the dynamic behavior, is given in Reference 6.

LINCOLN EXPERIMENTAL SATELLITES

LES-5 (Lincoln Experimental Satellite No. 5) is a cylindrical satellite in an equatorial orbit slightly below synchronous altitude, moving approximately 15° /day. The satellite polar axis is normal to the orbit plane. The 66" (1.68 m)-long, 49" (1.24 m) diameter satellite, shown in Figure A5, has two banks of solar cells, each 16 7/8" (42.9 cm) long, and two bands, painted white as part of the thermal control design, each 14 7/8" (37.8 cm) long. The diffuse reflectivity coefficient of the white painted panels is estimated to have decreased from its initial value of 0.8 to a value of 0.5 because of deterioration due to ultraviolet radiation. There are no large antenna structures.

The diffuse reflection then gives

$$\rho A F(\Phi) = 2 \times .07 \times .429 \times 1.24 \times \frac{1}{4} = .0186 \text{ m}^2$$

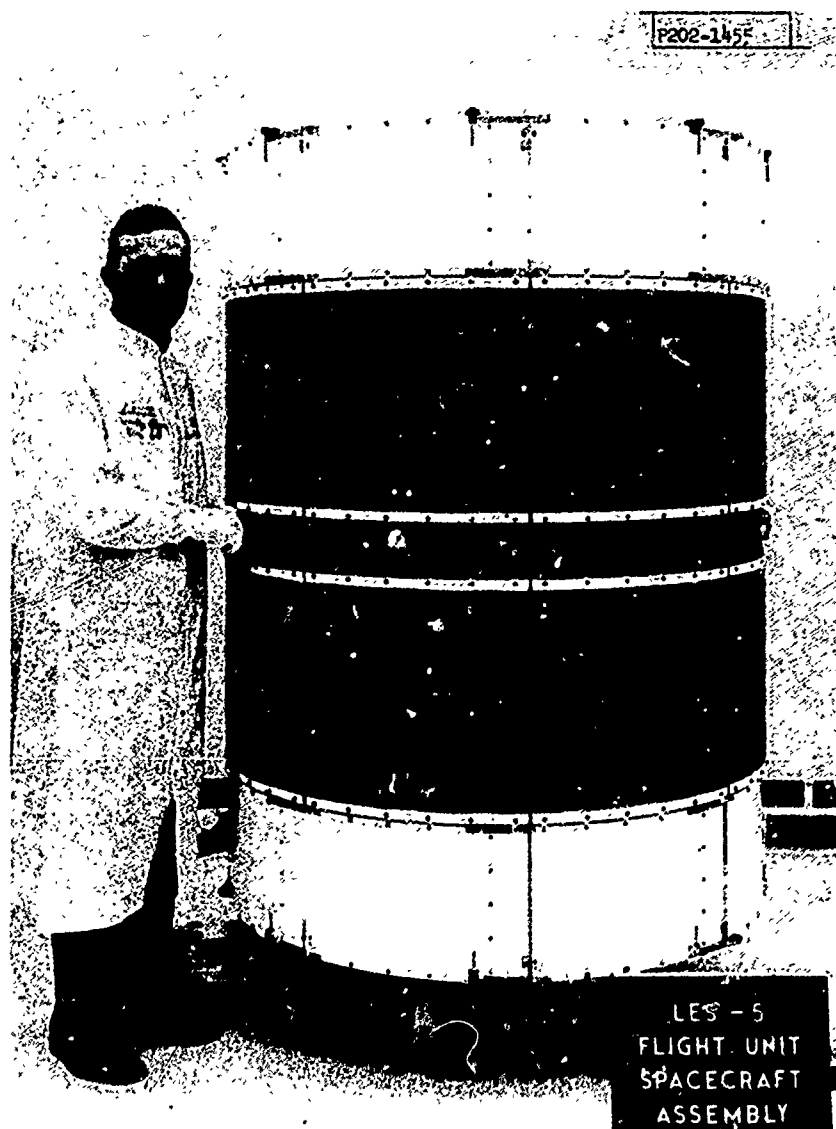


Fig. A5. Photograph of LES-5.

for the solar cells, and

$$\rho A F(\Phi) = 2 \times .5 \times 1.24 \times .378 \times \frac{1}{4} = .2344 \text{ m}^2$$

for the thermal control panels. This gives a visible magnitude of

$$m_v = 11.07 - 2.5 \log [.0186 + .2344]$$

$$m_v = 12.6^m$$

for the diffuse reflection.

The specular reflection from a line of solar cells 2 cm wide and 42.9 cm long gives

$$\rho A F(\Phi) = .15 \times .02 \times .429 \times \frac{4}{\pi (.0093)^2} = 18.9$$

which, in turn, gives a visible magnitude of

$$m_v = 11.07 - 2.5 \log 18.9$$

$$m_v = 7.9^m$$

No estimate for specular reflection from the thermal control panels is attempted.

LES-6 (Lincoln Experimental Satellite No. 6) is in 1 × synchronous, equatorial, approximately stationary orbit, located at longitude 38° West (Satellite Identification No. 3431).⁴ It is a cylindrical body of the same size as LES-5 (1.68 m long by 1.25 m in diameter), but has four bands of solar cells, as shown in Figure A6. Each band is 37.7 cm long and is made up of columns of cells, some of which are 2 cm wide and some 1 cm wide. The white thermal control paint has probably deteriorated to a diffuse reflection coefficient of 0.5.

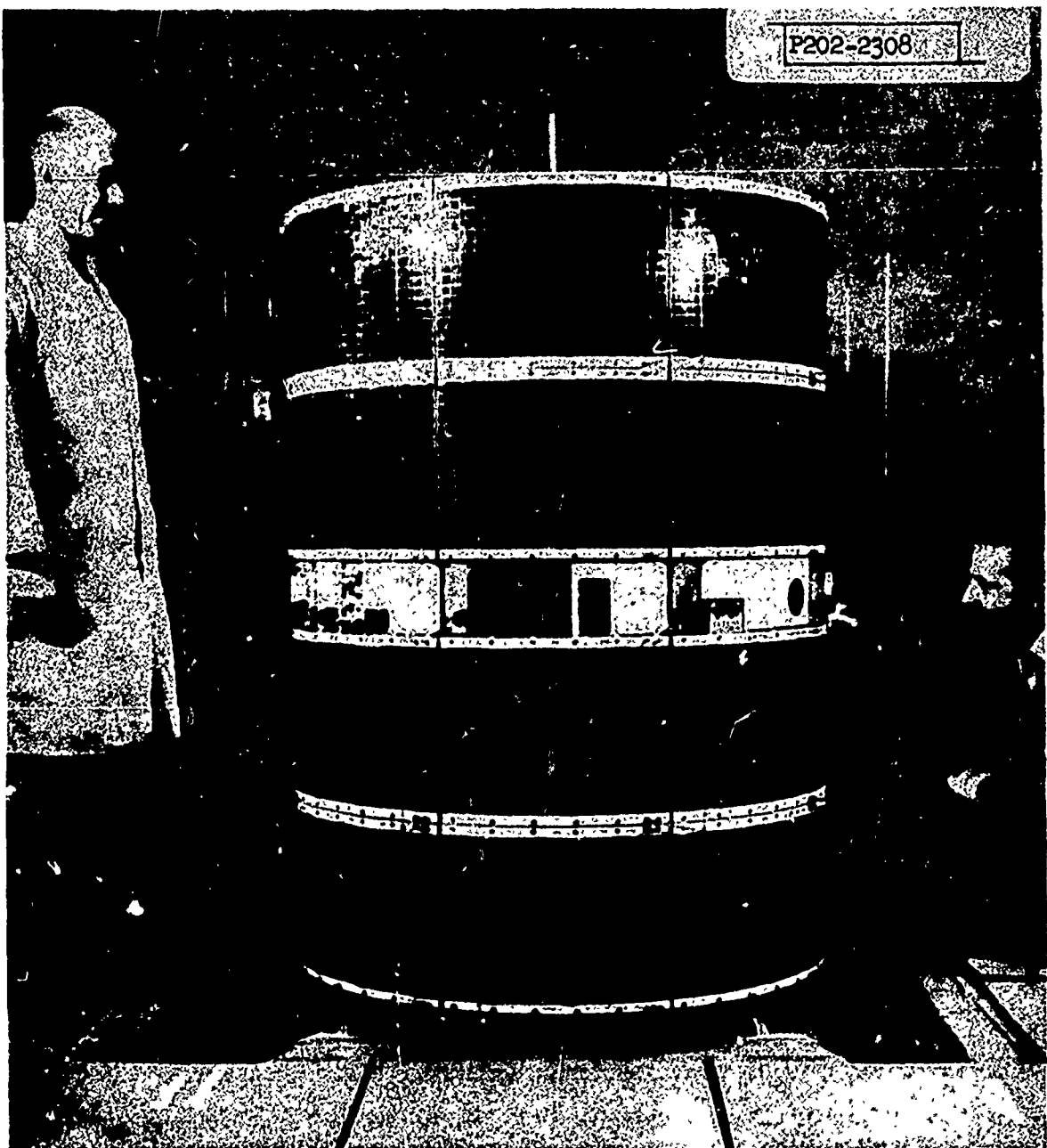


Fig. A6. Photograph of LES-6.

The diffuse reflection from the solar cell panels gives

$$\rho A F(\Phi) = 4 \times .07 \times .377 \times 1.24 \times \frac{1}{4} = .0327 \text{ m}^2 .$$

The view panel, at the center, is 6" (15.2 cm) wide and approximately 60 percent of it is painted white. There are eight bolting strips, each 1" (2.54 cm) wide also painted white. This gives, for diffuse reflection

$$\begin{aligned} \rho A F(\Phi) &= .6 \times .5 \times .152 \times 1.24 \times \frac{1}{4} + 8 \times .5 \times .0254 \times 1.24 \times \frac{1}{4} \\ &= .0456 \text{ m}^2 . \end{aligned}$$

The visible magnitude of the diffuse reflection is then

$$m_v = 11.07 - 2.5 \log [.0327 + .0456]$$

$$m_v = 13.8 .$$

The specular reflection from a column 37.7 cm long and 2 cm wide gives

$$m_v = 11.07 - 2.5 \log .15 \times 0.02 \times .377 \times \frac{4}{\pi(.0093)^2}$$

$$m_v = 8.0 ,$$

and from a 1 cm wide column of the same length,

$$m_v = 8.8 .$$

LINCOLN CALIBRATION SPHERE⁷

Finally, we consider a few RSOs with other than $1 \times$ synchronous, equatorial, stable orbits. LCS-1, the Lincoln Calibration Sphere (Satellite Identification No. 1361),⁴ is a highly polished metal sphere with cross sectional area of 1 m^2 in a circular orbit 2800 km above the earth's surface. The sphere, intended for radar calibration and not for optical studies, we assume to have a diffuse reflection coefficient of 0.5. Therefore

$$\begin{aligned} m_v &= -26.78 + 5 \log R - 2.5 \log \rho A F(\Phi) \\ &= -26.78 + 5 \log 2.8 \times 10^6 - 2.5 \log 0.5 \times 1 \times \frac{2}{3\pi} \\ m_v &= 7.9 \end{aligned}$$

is the visible magnitude of the diffuse reflection. For specular reflection the phase function, $F(\Phi)$, is equal to $1/4$ and, with a specular reflection coefficient of 0.5

$$m_v = 9.0$$

INTERPLANETARY MONITORING PLATFORM SATELLITE⁸

The Interplanetary Monitoring Platform Satellite (specifically IMP-6, Satellite Identification No. 5043)⁴ shown in artist's conception in Figure A7, consists of a 16-sided drum-shaped body, 136 cm in diameter and 150 cm high. Each flat on the cylindrical surface is a panel divided into four sections, each approximately 38 cm long and three of which are covered with solar cell panels ≈ 27 cm wide. There are several long (46 m) sectioned booms, extending from the sides of the spacecraft. These are metal, presumably polished and several cm in diameter. The structure is spinning at a rate of 12 rpm. Apogee is 1.975×10^5 km and perigee 7.7×10^3 km.

16-9-4284

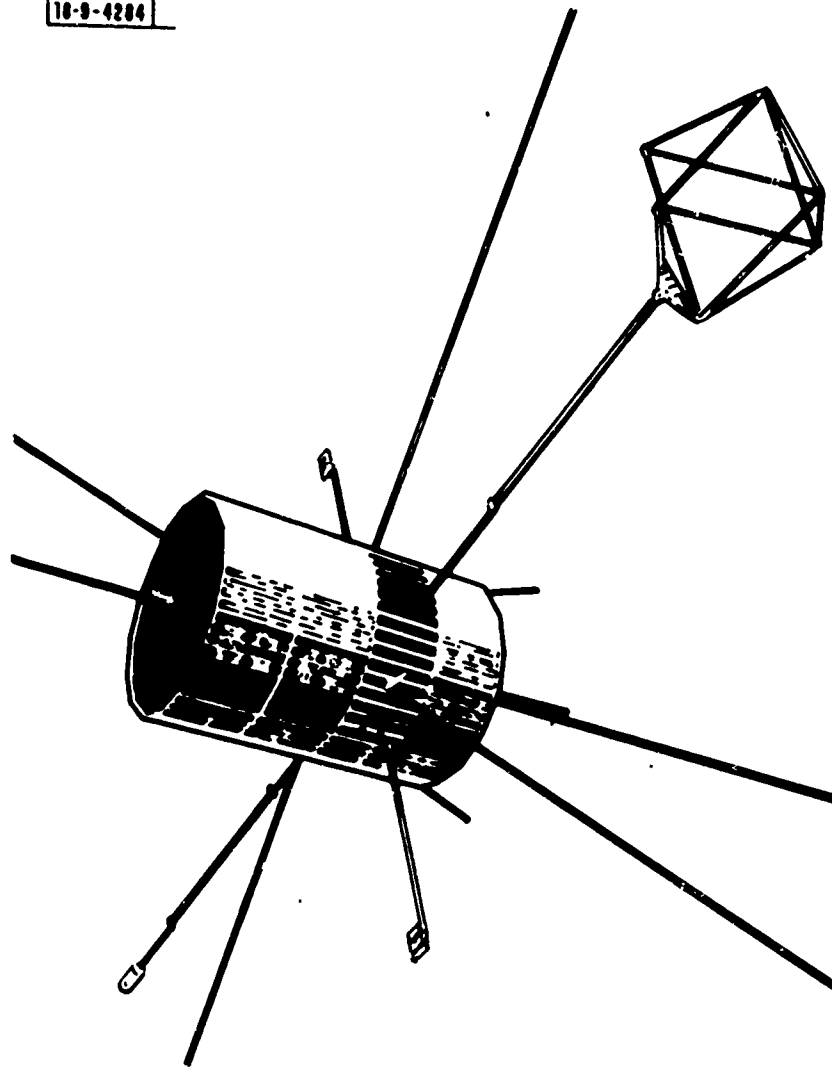


Fig. A7. Drawing of IMP-6 Satellite.

The diffuse reflection is from a series of flat panels with ϕ_1 and ϕ_2 equal to 0° (1), 22.5° (2), 45° (2) and 67.5° (2) at the zenith in full phase with one column of panels pointing directly at the earth. The diffuse reflection is then

$$\sum \rho A F(\Phi) = .07 \times 3 \times .38 \times .27 \left[\frac{1}{\pi} (1 + \sin^2 22.5^\circ + \sin^2 45^\circ + \sin^2 67.5^\circ) \right]$$

$$= .0171 \text{ m}^2 .$$

The visible magnitude of the diffuse reflection from the solar panels then is

$$m_v = -26.78 + 5 \log R - 2.5 \log 0.0171$$

$$m_v = -22.36 + 5 \log R ,$$

which ranges from $m_v = 19.^m_1$ at apogee to $m_v = 12.^m_1$ at perigee.

The specular reflection from one of the solar panels is

$$m_v = -26.78 - 2.5 \log .15 \times .38 \times .27 \times \frac{4}{\pi(.0093)^2} + 5 \log R$$

$$= -32.67 + 5 \log R$$

which ranges from $8.^m_8$ at apogee to $1.^m_8$ at perigee. The observed specular reflections should be several magnitudes lower because of the dispersion of the solar cell normals.

Let us assume that one of the booms has a circular cross section, 10 cm in diameter, 15 m long, and the diffuse and specular reflection coefficients are 0.5. Then for diffuse reflection

$$m_v = -26.78 + 5 \log R - 2.5 \log .5 \times .1 \times \sqrt{2} \times \frac{1}{4}$$

$$m_v = -24.96 + 5 \log R$$

which equals

$$m_v = \begin{cases} 16.^m.5 & \text{at apogee} \\ 9.^m.5 & \text{at perigee} \end{cases}$$

for the diffuse reflection.

For the maximum specular flash from the boom

$$F(\Phi) = \frac{\alpha(t)}{4\Delta}$$

where

$$\alpha(t) = \frac{8}{\pi} \sqrt{\frac{t}{t_0} \left(1 - \frac{t}{t_0}\right)} \quad \text{during the flash.}$$

During the flash $\alpha(t)_{\max} = 1.25$. Then the magnitude is

$$\begin{aligned} m_v &= -26.78 - 2.5 \log .5 \times .1 \times 15 \times \frac{1.25}{4 \times .0093} + 5 \log R \\ &= -26.78 - 3.50 + 5 \log R \end{aligned}$$

which equals

$$m_v = \begin{cases} 11.^m.2 & \text{at apogee} \\ 4.^m.5 & \text{at perigee} \end{cases}.$$

MOLNIYA SATELLITES

Finally, let us consider the Molniya series of satellites. These are Russian communication satellites in high-inclination orbits with periods of 717 minutes. The altitude varies from 40,000 km at apogee to 500 km at perigee. The Molniya 1 and 2 series are similar; a drawing of one of the Molniya 2 series is shown in Figure A8.

TN 1974-23 (A8)

SPECULAR

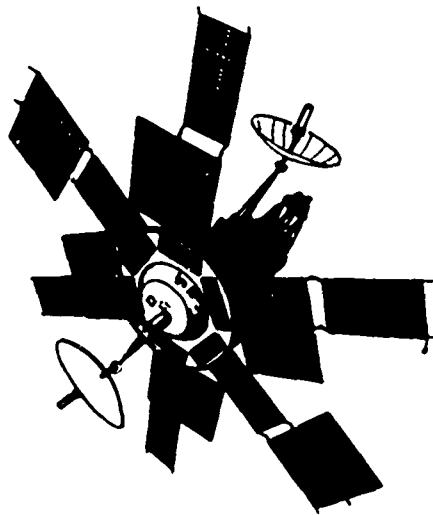
PADDLES: $2^m 9$.

DIFFUSE

PADDLES: $12^m 2$

CONE: $12^m 1$

TOTAL DIFFUSE:
 $11^m 5$.



VISIBLE MAGNITUDES: FULL PHASE AT 40,000 km.

SOLAR CELLS: $\rho_{\text{DIFFUSE}} = 0.07$ $\rho_{\text{SPECULAR}} = 0.15$.

Fig. A8. Molniya 2 Satellite.

The Molniya 2 series probably has different antennas than the two parabolic antennas shown in the figure. The satellite is oriented in space so that the solar panels, with a total area estimated to be on the order of 20 m^2 , always point directly at the sun. The principal source of the light reflected is from the panels, since the rest of the structure is shadowed. In the calculations below the end of the satellite is assumed to be a hemisphere, with a diffuse reflection coefficient of 0.5.

For the solar panels

$$\rho A F(\Phi) = .05 \times 20 \times \frac{1}{\pi} = 0.446$$

for diffuse reflection at full phase. For the hemisphere

$$\rho A F(\Phi) = .5 \times \frac{\pi(1.5)^2}{4} \times \frac{2}{3\pi^2} = .060.$$

Then

$$m_v = -26.78 + .74 + 5 \log R$$

which equals

$$m_v = \begin{cases} 12.^m0 & \text{at apogee} \\ 2.^m1 & \text{at perigee} \end{cases}.$$

It should be noted that these calculations assume the RSO to be at the zenith and at full phase. For a satellite 500 km above the surface of the earth this is obviously impossible. As pointed out in Figure 2, the magnitude does not change rapidly with plane angle θ , for cylindrical or spherical bodies. However for flat plates the reflected light in the direction of the observer goes to zero as the latitude, with respect to the plate surface, of either the sun or the observer goes to 0° . Figure A9 shows the geometry involved for the Molniya solar panels in calculating the changes in magnitude with the observer latitude. Note that since the solar panels always point

$$\Delta m_v = -2.5 \log F(\Phi)$$

$$\Phi = \pi - \beta$$

WHERE

$$\cos \beta = \sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos \theta$$

IF $\pi - \beta > \frac{\pi}{2}$, NO LIGHT OBSERVED

IF $\pi - \beta < \frac{\pi}{2}$

$$\Delta m_v = -2.5 \log \frac{1}{\pi} \cos(\pi - \beta)$$

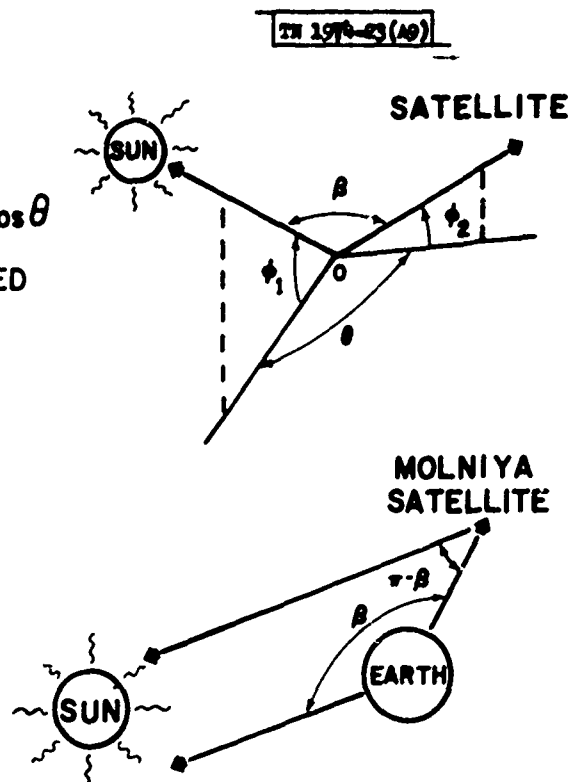
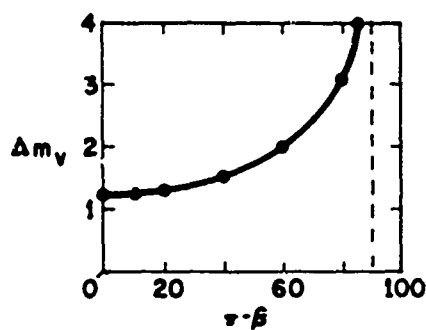


Fig. A9. Geometry for calculating visibility of Molniya solar panels.

at the sun, the magnitude can be calculated in terms of the phase angle, β , the satellite-observer-sun angle. The change in magnitude is shown in the graph at the lower left of Figure A9.

Although the satellite is oriented with the solar panels facing directly at the sun, since the paddles are probably not in a perfect plane, there is a possibility of observing specular reflections when the satellite is near full phase. Since there are 18 panels (Figure A8), the area of each is approximately 1 square meter. The magnitude of the specular reflection from a single panel is then

$$m_v = -26.78 - 2.5 \log .15 \times 1 \times \frac{4}{\pi(.0093)^2} + 5 \log R$$

$$m_v = -35.14 + 5 \log R$$

or

$$m_v = \begin{cases} 2.9^m & \text{at apogee} \\ -6.6^m & \text{at perigee} \end{cases}$$

These magnitudes would be increased, as pointed out for other panels, by dispersion of the solar cell normals.

Finally, in Table IA we include a list of RSO's, with the satellite identification number and orbit parameters and note whether they have been observed by radar and/or optical techniques. Where the information is available, the magnitude observed by R. Weber and T. H. Brooks of this Laboratory has been listed. In comparing with the calculations presented in this appendix, we note that the observed magnitude is always greater than the calculated magnitude, as is generally expected because of phase angle corrections.

TABLE IA
SATELLITES OBSERVED WITH RADAR AND OPTICAL TECHNIQUES

Satellite	Ident Number	Orbit Parameters				Observed by Radar Techniques	Observed by Optical Techniques	Observed Magnitude	Maximum Calculated Diffuse Magnitude	Maximum Calculated Specular Magnitude
		Period (min)	Apogee/Perigee (km)	Inclination (deg)	Location (Lat-Lon)					
ATS-1	2604	1436.0	35838/35738	5.7	149.0 W	x	x		14 ^m 5	6 ^m 6
ATS-3	3029	1436.0	35897/35671	4.1	69.1 W	x	x		14 ^m 5	6 ^m 6
ATS-5	4068	1436.0	35864/35711	1.1	105.0 W	x	x	14 ^m 3	14 ^m 1	7 ^m 5
Lincoln Laboratory LFS-5	3431									
LES-6	1361	145.5	2798/2775	32.1	38.0 W	x	x		12 ^m 6	7 ^m 9
Calibration Sphere									13 ^m 8	8 ^m 0
Intelsat IIF-4	2960	1436.0	35840/35774	4.7	201.0 E	x			7 ^m 9	9 ^m 0
Intelsat IIF-2	3623	1436.0	35802/35774	3.7	258.0 E	x				
Intelsat IVF-2	4881	1436.0	35794/35782	0.1	340.0 E	x	x	16 ^m 5	14 ^m 6	6 ^m 6
Intelsat IVF-3	5709	1436.0	35792/35788	0.1	336.6 E	x	x		12 ^m 8	5 ^m 8
Intelsat IVF-7	6796	1436.0	35800/35785	0.3	330.0 E	x	x		12 ^m 8	5 ^m 8
Comsat Rocket Body	5816	654.3	36604/569	27.9		x				
Comsat Rocket Body	4882	654.3	36502/671	28.3		x				
Comsat Rocket Body	6058	653.5	36587/543	26.2		x				
PAGEOS-1	2253	179.9	4283/4176	86.9		x				
IMP-6	5043	5968.0	197540/7700	33.0			x		19 ^m 1	11 ^m 2
Rocket Body	6792	697.3	38908/436	63.3			x			
Intelsat IIF-1	2514	719.0	37225/3178	17.9			x			
Molnlya-1 (21)	6231	717.7	39874/478	65.9		x	x	11 ^m 3	12 ^m 0	2 ^m 9
Molnlya-2 (7)	6877	717.9	39860/503	62.8			x		12 ^m 0	2 ^m 9

TABLE IA (continued)

Satellite	Ident Number	Orbit Parameters				Observed by Radar Techniques	Observed by Optical Techniques	Observed Magnitude	Maximum Calculated Diffuse Magnitude	Maximum Calculated Specular Magnitude
		Period (min)	Apogee/Perigee (km)	Inclination (deg)	Location (for syn)					
Molniya-2 (6)	6722	717.7	39970/385	65.6			x		12 ^m 0 *	2 ^m 9 *
Molniya-2 (5)	6418	717.6	39752/598	65.6			x		12 ^m 0 *	2 ^m 9 *
Molniya-1 (46)	4779	717.5	39177/1168	65.4			x	13 ^m 3	12 ^m 0 *	2 ^m 9 *
Molniya-1 (22)	6294	717.7	39800/553	65.0			x	12 ^m 2	12 ^m 0 *	2 ^m 9 *
Molniya-2 (4)	6308	717.7	39886/467	65.4			x	12 ^m 6	12 ^m 0 *	2 ^m 9 *
Molniya-1 (26)	6958	737.5	40880/447	62.7		x			12 ^m 0 *	2 ^m 9 *
Molniya	6805	717.7	39880/417	65.4					12 ^m 0 *	2 ^m 9 *
ELEKTRON IV	830	1314.0	65609/1108	59.6		x				

NOTE: Those magnitudes marked with * correspond to the magnitude at apogee.